XMM-NEWTON SPECTROSCOPY OF THE ACCRETION-DRIVEN MILLISECOND X-RAY PULSAR XTE J1751-305 IN OUTBURST

J. M. MILLER[1], R. WIJNANDS[1,6], M. MÉNDEZ[2], E. KENDZIORRA[3] A. TIENGO[4], M. VAN DER KLIS[4], D. CHAKRABARTY[1], B. M. GAENSLER[5], AND W. H. G. LEWIN[1]

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ABSTRACT

We present an analysis of the first high-resolution spectra measured from an accretion-driven millisecond X-ray pulsar in outburst. We observed XTE J1751–305 with *XMM-Newton* on 2002 April 7 for approximately 35 ks. Using a simple absorbed blackbody plus power-law model, we measure an unabsorbed flux of $6.6 \pm 0.1 \times 10^{-10}$ erg cm^{-2} s^{-1} (0.5–10.0 keV). A hard power-law component ($\Gamma = 1.44 \pm 0.01$) contributes 83% of the unabsorbed flux in the 0.5–10.0 keV band, but a blackbody component ($kT = 1.05 \pm 0.01$ keV) is required. We find no clear evidence for narrow or broad emission or absorption lines in the time-averaged spectra, and the sensitivity of this observation has allowed us to set constraining upper-limits on the strength of important features. The lack of line features is at odds with spectra measured from some other X-ray binaries which share some similarities with XTE J1751–305. We discuss the implications of these findings on the accretion flow geometry in XTE J1751–305 and the geometries inferred in other neutron star systems.

1. INTRODUCTION

Millisecond radio pulsars are thought to be created in neutron star low-mass X-ray binaries (LMXBs). In those LMXBs, accreting matter may spin-up the neutron star (see, e.g., Bhattacharya & van den Heuvel 1991). Therefore, it is expected that millisecond pulsars should also be found in LMXBs during the accretion phase of the binary as X-ray pulsars. Although evidence for rapidly spinning neutron stars in LMXBs was inferred from the burst oscillations which were seen during type-I X-ray bursts in several systems (see Strohmayer 2001 for a review), the detection of millisecond pulsations in persistent emission remained elusive for many years. In 1998, the first such system was discovered (SAX J1808.4–3658, which has a spin frequency of 401 Hz; Wijnands & van der Klis 1998a). This source was extensively studied due to its obvious importance for binary evolution scenarios and accretion flow geometries and dynamics (see, e.g., Wijnands & van der Klis 1998b and references therein). Although studies of SAX J1808.4–3658 yielded many interesting results, due to its unique nature it was difficult to place these within a broader context or to refine models.

This situation changed dramatically in the spring of 2002. Markwardt & Swank (2002a) reported the discovery of the second accretion-driven millisecond pulsar XTE J1751–305 (435 Hz) in the *Rossi X-ray Timing Explorer* (*RXTE*) bulge scan observation program. About one month after the discovery of this system, XTE J0929–314 was discovered (185 Hz; Remillard, Swank, & Strohmayer 2002.). The neutron stars in both systems are in orbit around a companion star, with an orbital period of ∼42 minutes (Markwardt & Swank 2002b; Galloway et al. 2002). These systems are very tight binaries and the inferred mass of their companion stars is very low (∼ 0.01 solar masses).

After the discovery of XTE J1751–305, we submitted a target-of-opportunity request to *XMM-Newton* for the purpose of studying this source with high-resolution spectroscopy in the 0.3–15 keV band. The X-ray spectrum of the first system — SAX J1808.4–3658 — could only be studied during outburst using *RXTE*, which is not sensitive below 3 keV and has only modest spectral resolution. Detailed analyses of orbitally-phase-resolved and pulse-phase-resolved spectra of XTE J1751–305 will be presented in future work. In this *Letter*, we present an analysis of the time-averaged EPIC-pn and Reflection Grating Spectrometer (RGS) data. The spectra obtained represent the first CCD- and gratings-resolution measurements from a millisecond X-ray pulsar in outburst.

2. OBSERVATION AND DATA REDUCTION

XMM-Newton observed XTE J1751–305 beginning on 2002 April 07.5 (UT). The EPIC-pn camera was operated in "timing" mode to prevent photon pile-up effects and to allow pulse-phase-resolved spectroscopy . The RGS was operated in the standard "spectral" mode. The "thin" optical blocking filter was selected for the EPIC cameras. The EPIC-MOS cameras were not operated in modes optimized for a source of this intensity, and we do not consider the MOS spectra here. The EPIC-pn and RGS data were reduced using SAS version 5.3.

We applied the standard reduction procedure "epproc" to produce a calibrated pn event list. In "timing" mode, the spatial information is compressed into one dimension. We extracted

[1]Center for Space Research and Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139–4307; jmm@space.mit.edu
[2]SRON, National Institute for Sapce Research, Sorbonnelaan 2, NL-3584 CA, Utrecht, NL
[3]Institut für Astronomie und Astrophysik, Abt. Astronomie, Universität Tübingen, Sand 1, D-72076, Tübingen, DE
[4]Astronomical Institute "Anton Pannekoek", University of Amsterdam, Kruislaan 403, NL-1098 SJ Amsterdam, NL
[5]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
[6]Chandra Fellow

source data in a rectangle (with a width of 37”) along the length of the CCD, and background data from adjacent regions. We further filtered the data such that only “single” and “double” events were selected. The net pn exposure was 33.7 ks. Using LHEASOFT version 5.1, the tool “grppha” was used to rebin the spectrum to require a minimum of 20 counts per bin. For spectral analysis, we used the trial “timing” mode redistribution and ancillary response functions developed by the EPIC-pn calibration team.

We applied the standard reduction procedure “rgsproc” to produce calibrated RGS event lists, first-order spectra, and response functions. Periods of high instrumental background were excluded, giving a net RGS exposure of 34.2 ks. The RGS spectra were grouped to require at least 20 counts per bin.

3. ANALYSIS AND RESULTS

Preliminary spectroscopic results from this *XMM-Newton* observation were reported in Miller et al. 2002a and Miller et al. 2002b; however, the analysis presented here is significantly expanded and refined. The accurate position of XTE J1751–305 was reported by Ehle et al. (2002), also based on analysis of this observation (R.A. = $17h51m13.5s$, Decl. = $-30°37'22''$, equinox 2000.0). The EPIC-pn and RGS spectra were analyzed using XSPEC version 11.1. All errors quoted in this paper are 90% confidence errors. Note that systematic errors are not added to the spectra to account for flux calibration uncertainties. We characterize the broad-band spectrum by modeling the EPIC-pn spectrum, and search for narrow emission lines and absorption lines and edges using the RGS spectra.

3.1. *The EPIC-pn Spectrum*

In the 0.3–0.6 keV band, we note broad deviations which appear as absorption but are not satisfactorily accounted for by allowing enhanced elemental abundances in an ISM absorption model. The characterization of the EPIC-pn response in timing mode is preliminary and so we speculate that this may be a response issue. We therefore examined the EPIC-pn spectrum in the 0.6–10.0 keV band. The average count rate (79.36 counts s^{-1}) is well below that at which photon pile-up occurs in timing mode (1500 counts s^{-1}).

We first considered a model consisting of blackbody and power-law components, modified by neutral absorption in the ISM (using the “phabs” model in XSPEC). We measure a best-fit equivalent hydrogen column density of $N_H = (9.8 \pm 0.1) \times 10^{21}$ atoms cm^{-2}. The blackbody temperature obtained is moderate: $kT = 1.05 \pm 0.01$ keV. For spherical symmetry, this translates into a blackbody radius of $R = f^2 \times 3.01^{+0.09}_{-0.06}$ (d/10 kpc) km, where the spectral hardening factor f is the ratio of the color temperature and the effective temperature, and d is the distance to the source. The measured power-law index is very hard: $\Gamma = 1.44 \pm 0.01$; the normalization is $(6.4 \pm 0.1) \times 10^{-2}$ (photons keV^{-1} cm^{-2} s^{-1} at 1 keV). This model produces an adequate fit to the data: $\chi^2/\nu = 1.107$ (where ν is the number of degrees of freedom; $\nu = 1884$ for this model; see Figure 1). We note that a simple power-law model returns a very poor fit ($\chi^2/\nu > 4, \nu = 1886$); the soft blackbody component is strongly required by the data.

With this simple but standard model, we obtain an unabsorbed 0.5–10.0 keV flux of $(6.6 \pm 0.1) \times 10^{-10}$ erg cm^2 s^{-1}, or (0.170 ± 0.004) photons cm^{-2} s^{-1}. The hard power-law component contributes 83% of the unabsorbed flux in the 0.5–10.0 keV band.

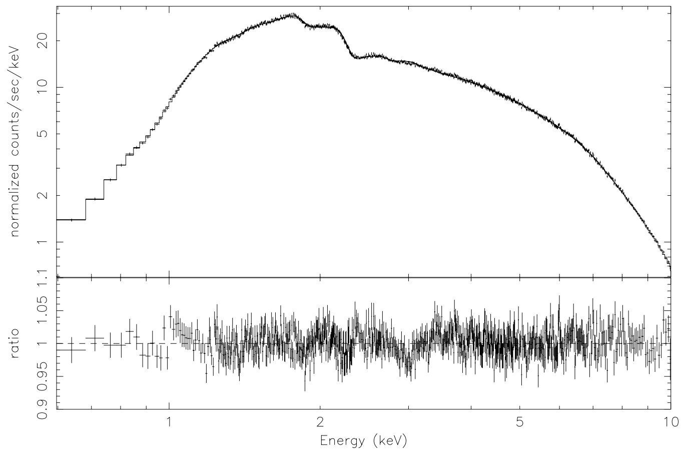

FIG. 1.— The EPIC-pn spectrum of XTE J1751–305, fit with a model consisting of blackbody and power-law components modified by photoelectric absorption (see Section 3 for details). The spectrum and data/model ratio shown above are rebinned for visual clarity.

We also fit the EPIC-pn spectrum with the “compTT” Comptonization model (Titarchuk 1994), which attempts to account for the Compton-upscattering of cool photons in a hot corona self-consistently. This model does not provide an acceptable fit by itself ($\chi^2/\nu = 2-4, \nu = 1884$). We find a degeneracy between a cool corona ($kT \sim 3$ keV) with high optical depth ($\tau \sim 8$), and a hot corona ($kT \sim 40$ keV) with lower optical depth ($\tau \sim 1$), each up-scattering a seed photon distribution peaking between kT =0.5–0.6 keV. In both cases, the parameters of the model are poorly constrained.

We tried fitting a blackbody component in addition to compTT. This model might correspond to a scenario in which the blackbody emission region is only partially covered by the corona along our line of sight, or a scenario in which the corona is continuous but inhomogeneous. Again, this model did not provide a good description of the data ($\chi^2/\nu \sim 2$).

In a spectral survey of low-mass X-ray binaries observed with *ASCA*, Asai et al. (2000) report the possible detection of an Fe Kα line in the ultra-compact binary 4U 1820–30. The line was found to be ionized (E = 6.6 ± 0.1 keV), broad (FWHM = $0.7^{+0.2}_{-0.5}$ keV), and weak ($W_{K\alpha} = 33^{+12}_{-11}$ eV). Assuming a line of equivalent FWHM in the 6.40–6.97 keV range (Fe I — Fe XXVI), we measure a 95% confidence upper-limit of just 6 eV in the EPIC-pn spectrum of XTE J1751–305. No clear evidence exists for narrow or broad absorption lines or edges in the Fe Kα band.

3.2. *Pulse-Phase-Resolved Spectroscopy: First Results*

We applied the SAS task “barycen”, and using the binary system parameters reported by Markwardt et al. (2002) we produced spectra from the “high” and “low” parts of the pulse. We find that the model applied to the time-averaged spectrum is an acceptable description of these spectra (no convincing narrow or broad emission or absorption features are found). Interestingly, the slope of the power-law component is consistent in the two spectra but the normalization changes, and the blackbody component changes in temperature but not in normalization. Similar behavior was discovered in pulse-phase-resolved spectra of SAX J1808.4–3658 (Gierlinski, Done, & Barret 2002).

We note that a possible feature at approximately 2.9 keV appears to vary in width, intensity, and centroid energy in the “high” and “low” spectra; however, the error limits on the line

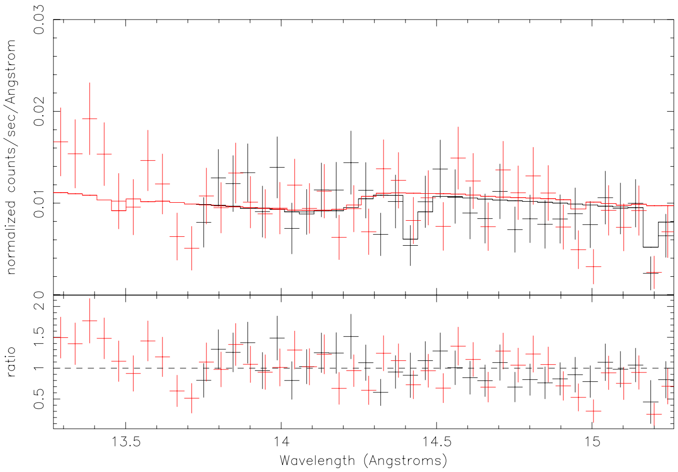

FIG. 2.— The RGS spectra of XTE J1751–30 (RGS-1 in black, RGS-2 in red; both are rebinned for clarity and narrow features are instrumental) fit locally in the region of the Ne K edge (14.25Å) with a simple power-law plus edge model. Above, the edge depth is fixed at the solar value; a trend in the data/model ratio is clearly visible. Fits made with a variable edge depth suggest Ne is likely under-abundant (see text).

parameters overlap. This feature is also visible in the time-averaged spectrum (see Figure 1). As there are no astrophysically abundant elements with transitions near this energy, it is tempting to associate this feature with a red-shifted absorption line from the neutron star surface (given the temperature of the blackbody, perhaps Fe XXV or Fe XXVI). Although an F-test finds that the addition of a Gaussian to model this feature is significant at the 7σ level of confidence in the "low" part of the pulse (3σ in the "high" part), a similar feature is apparent when the EPIC-pn spectrum of the Galactic black hole candidate XTE J1650–500 (Miller et al. 2002c) is fit using the same response matrix. It is likely that this feature is due to a defect in the timing-mode response matrix.

3.3. *The RGS Spectra*

We fit the RGS spectra with the best-fit model applied to the EPIC-pn spectrum. This model returns an acceptable fit to the data ($\chi^2/\nu = 1.314, \nu = 1463$); when the parameters were allowed to vary, the power-law could not be constrained. We therefore conclude that our model for the EPIC-pn spectrum is also valid in the RGS band, and focus on a search for narrow features in the RGS spectra.

We analyzed the RGS spectra in contiguous 3Å slices for narrow emission or absorption lines. In each 3Å slice, a simple power-law plus ISM edge(s) model was fit to the data. We find no convincing evidence for narrow absorption features in this band (0.3–2.5 keV, or 5–40Å). However, we note that at energies below $\sim$0.6 keV ($\sim$21Å) the sensitivity is low due to the relatively high equivalent column density along the line of sight to XTE J1751–305.

In order to explore the possibility of a Ne–rich degenerate donor on this compact binary (see, e.g., Juett, Psaltis, & Chakrabarty 2001), we fit the RGS spectra around the position of the Ne K edge at 14.25Å (see Figure 2). Using the cross-sections of Verner et al. (1993) and solar abundances relative to H as per Morrison & McCammon (1983), we find that Ne may be *under*-abundant in XTE J1751–305: the 95% confidence upper-limit is that the abundance of Ne is only 77% of the solar value. It is clear that the fit in Figure 2 — which was

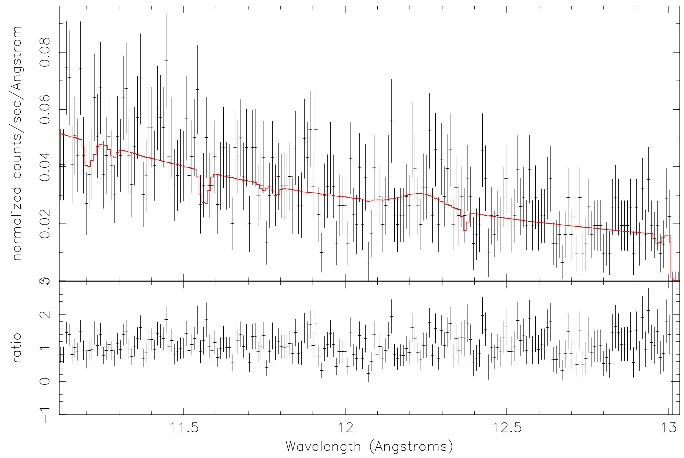

FIG. 3.— The RGS-2 spectrum of XTE J1751–305 in the region of the Ne X Ly-α line at 12.13Å, fit with a simple power-law plus gaussian model. Our best fit model does not require an emission line within 12.13 ± 0.1Å, assuming a FWHM equivalent to the prominent Ne X Ly-α emission line seen in the 42-minute X-ray pulsar 4U 1626–67 (Schulz et al. 2001). Narrow features are instrumental.

made assuming a solar Ne abundance — does not allow for an optimal characterization of the local spectrum.

The binary X-ray pulsar 4U 1626–67 also has a 42-minute orbital period. Moreover, the distance to this system may be close to 8 kpc (Chakrabarty 1998); we anticipate a Galactic center location for XTE J1751–305 and therefore a similar distance. A *Chandra* High Energy Transmission Grating Spectrometer (HETGS) spectrum of 4U 1626–67 reveals broadened emission lines and Doppler-shifted line pairs. The Ne Ly-α line (12.13Å) is particularly strong (a flux of $8.15 \pm 0.93 \times 10^{-5}$ photons cm^{-2} s^{-1} is measured; FWHM = 2860 ± 330 km s^{-1}). Assuming an equivalent FWHM is within 0.1Å of the expected Ne Ly-α wavelength, we examined the possibility of a similar broadened feature in XTE J1751–305 (see Figure 3). Using a Gaussian line model, the best-fit line strength is consistent with zero, and we measure a 95% confidence upper-limit on the flux from such a line of 6.3×10^{-5} photons cm^{-2} s^{-1}.

4. DISCUSSION

We have analyzed the first CCD- and grating-resolution X-ray spectra of a millisecond X-ray pulsar in outburst. We find no convincing evidence for broad or narrow emission or absorption features in the spectra (see Figure 1).

With our simple blackbody plus power-law model for the EPIC-pn spectrum, we find that the power-law component comprises 83% of the unabsorbed flux in the 0.5–10.0 keV band. The power-law component is hard: $\Gamma = 1.44 \pm 0.01$, but within a range typical for X-ray pulars (e.g., $\Gamma = 1.0$–1.5; White, Swank, & Holt 1983). We note that this index is significantly harder than that reported by Markwardt et al. (2002) from fits to *RXTE* spectra of XTE J1751–305 in outburst ($1.7 < \Gamma < 1.9$). This disparity is likely due to the fact that the absorbing column could not be reliably measured or a soft component detected for this relatively dim source with the *RXTE*/PCA (which has an effective lower energy range of $\sim$3 keV). Spectral evolution at higher energies may also contribute to this disparity; joint fits to the *XMM-Newton* and *RXTE* spectra in the future may resolve this matter.

The EPIC-pn spectrum requires a blackbody with $kT = 1.05 \pm 0.01$ keV and an implied emitting radius of $R = f^2 \times$

$3.01^{+0.09}_{-0.06}$ $(d/10\mathrm{kpc})$ km. The spectral hardening factor, f, which is the ratio of color temperature and effective temperature for neutron star atmospheres, depends on the ratio of the luminosity and the Eddington luminosity. It is fair to say that our knowledge of this spectral hardening is rather poor (for a discussion, see Lewin, van Paradijs, & Taam 1993). If f is less than 1.3, it would indicate that only part of the neutron star surface is involved. Therefore, although especially tantalizing in a source like XTE J1751–305, the implied emission radius cannot be considered as strong evidence that the emitting region is primarily confined to a hot spot.

Evidence for a weak Fe Kα line was reported in outburst spectra of the 401 Hz millisecond X-ray pulsar SAX J1808.4–3653 obtained with *RXTE* (Heindl & Smith 1998; Gierlinski, Done, & Barret 2002). As the orbital period of SAX J1808.4–3658 is 2 hours (Chakrabarty & Morgan 1998), the accretion disk in that system may be larger than in XTE J1751–305 and provide a larger cool reflecting volume for Fe Kα line production. However, this explanation is inconsistent with evidence for a weak Fe Kα emission line reported in *ASCA* spectra of the ultra-compact binary 4U 1820–30 (Asai et al. 2000). From the EPIC-pn spectrum of XTE J1751–305, we measure a 95% confidence upper-limit on the strength of a line (with FWHM = 0.7 keV) of just 6 eV. It is possible that an extremely hot, ionized corona (or the magnetosphere, if the coranae in these LMXBs is small or disrupted) which produces to the power-law component might also fully ionize the disk in XTE J1751–305, thereby preventing Fe Kα emission from the disk in this source.

The dispersed RGS spectra reveal no clear evidence for narrow emission or absorption lines. This may be due to the inclination of XTE J1751–305 (Markwardt et al. 2002 report no evidence of dips or eclipses), its low magentic field, and an ionized accretion flow.

In a *Chandra*/HETGS spectrum of the X-ray pulsar 4U 1626–67 (which has a 42-minute orbit like XTE J1751–305), a strong Ne Ly-α emission line was found (for some lines, Doppler-shifted pairs were observed; Schulz et al. 2001). The 95% confidence upper-limit on the flux of any such line in XTE J1751–305 is below the measured line flux in 4U 1626–67 (see Section 3.2 and Figure 3). Whereas the magnetic field in XTE J1751–305 is likely to be similar to that in SAX J1808.6–3658 ($B = (2-6)\times 10^{8}$ G; Wijnands & van der Klis 1998a), the magnetic field in 4U 1626–67 is likely much higher ($B = 3\times 10^{12}$ G, Orlandini et al. 1998). The stronger magnetic field in 4U 1626–67 may disrupt the inner disk, allowing cool material in the outer disk to be irradiated. A number of emission lines are seen in the eclipsing X-ray pulsar 2A 1822–371 (Cottam et al. 2001). It is possible that lines are produced in this source because the region of impact between the accretion stream and outer disk is irradiated by the central accretion region, though the magnetic field strength may also play a role ($B = (1-5)\times 10^{12}$ G, Jonker & van der Klis 2001).

Absorption lines from highly ionized Fe species have been reported in non-pulsing sources, including GX 13+1 (Sidoli et al. 2002), X 1624–490 (Parmar et al. 2002), and the eclipsing source MXB 1659–298 (Sidoli et al. 2001). These features may represent absorption in a highly ionized coronal volume, and may be observed in part due to relatively high inclinations. Outflowing material in GX 13+1 (suggested by the strong radio emission observed) may also be partly responsible for the absorption lines observed in this source. The lack of such features in the spectrum of XTE J1751–305 may also indicate that any coronal volume in this source is extremely hot and more ionized than similar geometries in other LMXBs.

Studies of the neutral Ne absorption edge in compact X-ray binaries — in which a neutron star must accrete from a degenerate companion — suggest that some systems may harbor a Ne–rich companion (for observational evidence, see Juett, Psaltis, & Chakrabarty 2001; for theoretical background, see Yungelson, Nelemans, & van den Heuvel 2002). Our analysis of the neutral Ne absorption edge in the RGS spectra of XTE J1751–305 suggests an abundance which is only 77% of the solar value (95% confidence upper-limit) along this line of sight (see section 3.2 an Figure 2). Given that the strong power-law component in this system may ionize much of the nearby material, an excess of neutral material might be particularly unexpected in this system.

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REFERENCES

Arnaud, K. A., 1996, Astronomical Data Analysis Software and Systems V, eds. G. Jacoby and J. Barnes, p17, ASP Conf. Series vol. 101
Asai, K., Dotani, T., Nagase, F., & Mitusda, K., 2000, ApJS, 131, 571
Bhattacharya, D., & van en Heuvel, E. P. J., 1991, Phys Rep., 203, 1
Bildsten, L., & Chakrabarty, D., 2002, ApJ, 557, 292
Campana, S., et al., 2002, ApJ, in press, astro-ph/0206376
Chakrabarty, D., 1998, ApJ, 492, 342
Chakrabarty, D., & Morgan, E. H., 1998, Nature, 394, 346
Ehle, M., et al., 2002, IAU Circ. 7872
Galloway, D. K., Chakrabarty, D., Morgan, E., & Remillard, R., 2002, ApJ, in press, astro-ph/0206493
Gierlinski, M., Done, C., & Barret, D., 2002, MNRAS, 331, 141
Heindl, W. A., & Smith, D. A., 1998, ApJ, 560, 35L
Juett, A. M., Psaltis, D., & Chakrabarty, D., 2001, ApJ, 560, L59
Lewin, W. H. G., van Paradijs, J., & Taam R. E., 1993, SSRv, 62, 223
Markwardt, C. B., & Swank, J. H., 2002a, IAU Circ. 7867
Markwardt, C. B., & Swank, J. H., 2002a, IAU Circ. 7870
Markwardt, C. B., Swank, J. H., Strohmayer, T. E., in 't Zand, J. J. M, & Marshall, F. E., 2002, ApJ, 575, L21
Miller, J. M., et al., 2002a, ATEL 90
Miller, J. M., et al., 2002b, ATEL 91
Miller, J. M., et al., 2002c, ApJ, 570, L69
Morrison, R., & McCammon, D., 1983, ApJ, 270, 119
Orlandini, M., et al., 1998, ApJ, 500, 163L
Parmar, A. N., Oosterbroek, T., Boirin, L., & Lumb, D., 2002, A & A, in press
Remillard, R. A., Swank, J., & Strohmayer, T., 2002, IAU Circ. 7893
Schulz, N. S., Chakrabarty, D., Marshall, H. L., Canizares, C. R., Lee, J. C., & Houck, J., 2001, ApJ, 563, 941
Sidoli, L., Oosterbroek, T., Parmar, A., N., Lumb, D., & Erd, C., 2001, A & A, 379, 540
Sidoli, L., Parmar, A. N., Oosterbroek, T., & Lumb, D., 2002, A & A., 385, 940
Strohmayer, T. E., 2001, AdSpR, 28, 511
Titarchuk, L., 1994, ApJ, 434, 313
Verner, D. A., Yakovlev, D. G., Band, I. M., & Trzhaskovskaya, M. B., 1993, ADNDT, 55, 233
White, N. E., Swank, J. H., & Holt, S. S., 1983, ApJ, 270, 711
Wijnands, R., & van der Klis, M., 1998a, Nature, 394, 344
Wijnands, R., & van der Klis, M., 1998b, ApJ, 507, 63L
Yungelson, L. R., Nelemans, G., & van den Heuvel, E. P. J., 2002, A & A, 388, 546